

ECONOMIC OPERATION OF ELECTRIC POWER SYSTEMS

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## INTRODUCTION

It should be the aim of all engineers to develop efficiency in its broader sense, that is, by the realization of maximum economy in design, construction and operation. The allocations of load to power plants and to the equipment within them greatly influences the production costs, and the method of loading should be such that electric energy is produced at the lowest possible cost consistent with the obligation of maintaining continuity of service.

In design, construction or operation of an electrical system, the object to be striven for is to provide all customers with a good quality of service at the least possible cost over the system as a whole. This result can be attained only through a careful and conscientious application of the principles of economics to all parts of the system. The new analytical and computing techniques which have resulted in significant annual savings in the production economy of electric utilities, should be employed. Several powerful tools which greatly enhance the engineer's capability of solving system problems should be considered.

## ESSENTIALS AND ECONOMIC DESIGN

The commercial success of any electrical undertaking depends upon the cost and reliability of the supply and unless power be supplied at a price having advantages over private or other methods of generation, business will not be forthcoming.

The importance of reliability can not be too highly emphasized and should take precedence over the cost of supply. Some of the features which are desirable for power supply operation and development are compact area, many large power consumers and few geographical obstacles. Some of the obstacles are lack of adequate low temperature circulating water, limited facilities for transport of coal and frequent electric storms of extreme violence.

The chief thing is to provide a station and electrical system at a minimum capital cost consistent with sound engineering which results in minimum operating costs throughout its useful life. It is necessary to take into consideration the commitments of the undertaking, the nature of the service for which the energy is required and the probabilities of future development. The whole aim in the building of a new power station should be to make progress in the economics of generation of electric power.

The plant installation is divided into two parts; the first, the boiler plant, converts the heat energy of the coal into steam; and the second, the turbine plant, converts the energy in the steam into electricity. The first process is carried out by the boiler plant and the second by the turbine plant.

If coal conservation were the most important factor then the highest thermal efficiency attainable irrespective of capital charges would be the aim. Present day practice implies that the efficiency attainable be balanced against capital and operating costs of the plant required to attain this efficiency. The

efficiency desired is therefore limited by economic considerations and is not a matter of engineering technique alone.

Apart from economic considerations it will be appreciated that the better way of comparing stations or plants is on the basis of heat consumption and not fuel consumption. Thermal efficiency is almost independent of the price of coal, whereas economic thermal efficiency or commercial efficiency is almost entirely dependent on the price of coal together with load factor.

In many of the existing stations the scrapping of boiler and turbine plant has been justified by the advance in efficiency of plant design, the high maintenance costs of an old plant, the possibility of failure due to age, and the increased capacity of large modern units which may be accommodated on the same site.

In the building of a power station, involving several millions of dollars capital, the time element becomes a factor of prime importance for the reason that until it is completed and in commercial operation, the capital involved may to all intents and purposes be considered idle and consequently unremunerative. It is therefore essential that a project of this magnitude should be completed as soon as possible in order to get a return on the capital invested.

It seldom happens that one power station site is like any other in every respect, consequently different problems present themselves in the design of each new station. The differences in the problems have in part been responsible for the lack of uniformity in design and layout. Although the design and layout is straight-forward in every way it is essential that the designer should be fully acquainted with the plant to be installed and so obtain the most economical layout.

Power station design, construction and operation are so indissolubly bound together that each go hand in hand. There are many ways in which the various

items of the plant may be arranged in relation to one another and it is necessary to know the behavior of such plants under normal and abnormal conditions of operation.

Power stations are of national importance and a reputation for absolute continuity of supply is worth a great many tons of coal per annum. High economy may imply high reliability whereas low economy may imply low reliability but the deficiency may be due to improper design. The engineer and architect should work hand in hand with an open mind for the hallmark of good design is simplicity.

The economics of electric power production and distribution make it essential that generation should be carried on in large central stations, the location of these playing an important part in the cost of energy generated. The ideal position is at the center of gravity of the "loads" on the distribution system, thus avoiding very long transmission lines. The shortening of the length of transmission lines and/or cables reduces the capital cost and losses associated with them, even with a lower thermal efficiency due to the use of cooling towers compared with a river side site some considerable distance from the load center.

While selecting a site, the following factors must be given special consideration:

- (1) The cost of land should be reasonable. Where a station must, of necessity be situated in or near a city, the cost of land is in general much higher than in urban or rural areas, and in addition it may be necessary to carry out property condemnation to obtain the requisite site area.

- (2) A plentiful supply of cooling water is desirable. The use of large and highly efficient cooling towers and multi-stage feed water heating has effected large reduction in the quantity of cooling water required. The water



may be taken from a river, sea, canal or sewage outfall. About 500 tons of cooling water are required for every ton of coal burned. Where cooling towers are employed a sufficient quantity of water to provide for makeup is necessary. Suitable water is also required for boiler feed purposes.

(3) Availability of inexpensive fuel and ample railway facilities for coaling and a suitable river or canal as an alternative for water-borne coal. In some cases it is possible to place a station near the coal mine and convey the coal almost direct from the shaft to the boiler bunkers.

(4) The civil engineering works involved should be a minimum. This implies a level site and a good foundation at a reasonable depth. If possible the site conditions should be such that piling or blasting is not required. A firm rock bottom not too hard is desirable. The site should not be surrounded by residential property and should be isolated to prevent danger from fire breaking out in, and spreading from neighboring buildings.

(5) Care should be taken to limit the possibility of nuisance to the neighboring property and its occupants, due to the emission of smoke, grit, noise, steam, water vapor, etc.

This condition may dictate the type of boiler plant it is possible to install; i.e., stokers in preference to pulverised fuel. Stokers appear to produce less "fly ash," and the duty of the flue gas cleaning plant is not nearly so severe as with pulverised fuel boilers.

(6) Facilities for the disposal of ashes, e.g., large areas of land near the site which are flooded and valueless for development, quarries, etc.

(7) At some later date it may pay to change the site of the station and supply the system from another station where power is produced at reduced cost.

(8) The rates and rents should be low and housing accommodations in the immediate neighborhood should be adequate.

(9) The surrounding country should afford ample room for the establishment of industries requiring large amounts of electricity at the lowest possible price. The geographical position should meet existing and anticipated future demands while access for both overhead and underground feeders is desirable.

(10) The choice of site should allow for economical extensions consistent with the estimated growth of load.

(11) In view of the rapid development of aerial warfare it may be essential to limit the capacity of stations and choose sites which are away from densely populated and industrial areas. The inter-connection of stations is a safeguard in this respect providing physical and electrical separation is included.

From this preview it will be appreciated that the choice of site is fundamental to the efficient supply of electricity and generally speaking may be of greater importance than the quality of plant installed on it. The plant can be replaced when it becomes inadequate or obsolete whereas the main features of the site, whether good or bad, are permanent.

The essential principles of electric power system design are: reliability, minimum operating and maintenance costs and minimum capital cost. These depend to large extent on the following: simplicity of design, sub-division of plant and apparatus, labor saving equipment, extensibility, and organization.

### Simplicity of Design

Simple and sound design and layout are desirable features in all sections of a station for good layout of the plant simplifies building and civil engineering works apart from aiding operation.

There should be a minimum of auxiliaries, a limited number of floor levels and sufficient area to provide spacious but economical layout of the plant.



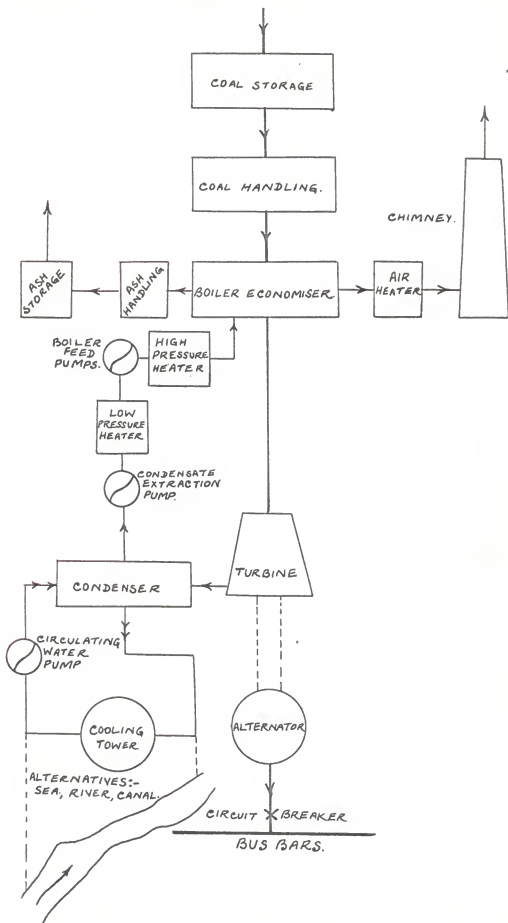


Fig. 1. Power system flow sheet. (From Electric Power Stations by Carr)

These are important features of simplification and should always be borne in mind. A compact station, if well planned, is just as accessible and easy to operate as one in which the floor area, though considerably greater, is not used to best advantage. The volume and floor area per K.W. should be a minimum consistent with operating conditions. The design of the plant should be as simple as possible even at the expense of striving for thermal records. In carrying out the detailed design and in the construction of a power station, the features of simplicity, compactness and commercial efficiency should always be kept in mind. Thermal economy should go hand in hand with overall financial efficiency.

A standardized design for each unit may not always be economical due to rapid advances in science, but the value of simplicity and standardization should be carefully considered before making radical changes. Generally speaking, a simple design of plant is relatively low in first cost, reliable and does what is expected of it. On the other hand, designs departing from general practice have had many difficulties and have usually required a number of years of operating experience to bring them up to expectations.

Economical operation and performance together with convenience of access to all essential apparatus and auxiliaries and ease of control are important features. In designing a station it is of great importance to standardize as far as possible since the capital cost is reduced, space is saved, repairs and maintenance charges reduced and administration is facilitated. This is an important feature in any station but more so when the station is abroad and where spare materials take a considerable time to be delivered to the site. It would be unwise for a country far from manufacturing centers to adopt frills and technical novelties. Reliability is of primary importance, economy being sought in directions other than ultimate thermal efficiency.

### Sub-division of Plant and Apparatus

Sub-division of plant and apparatus is essential if complete shut down is to be guarded against. Furthermore, it promotes safety in operation and facilitates maintenance. Sections of the plant may be completed and put into service separately, thus reducing time and cost of construction. The trend appears to be towards one boiler per turbine and one alternator for each section of feeders with arrangements for inter-connection under maintenance or emergency conditions.

### Labor-Saving Equipment

The inclusion of labor saving equipment is desirable providing reliability is unimpaired and the cost is reasonable. The automatic equipment installed should be reliable and such that the human element may be safely dispensed with, particularly where it performs important functions. In some cases it may be justifiable to include both automatic and manual controls so that the latter is always available in case of emergency.

### Extensibility

Usually the future requirements of a power station are not definitely known, but the present types of plant have now come within such narrow limits of maximum possible efficiency that no great changes are likely to take place in the near future. If careful consideration is given to the initial installation, then additions should not affect the existing plant to any great extent. Speaking generally, a power station may be extended without appreciably affecting the ultimate cost and should therefore be commenced on the smallest scale possible.

## Organization

The organization is the structure through which the functions of management are applied, and the form it takes determines the responsibilities and relationships which each individual bears to another. In the power station it is the duty of engineers to deal with the problems of design and construction of plant and buildings, the installation, maintenance and operation of the power plant and equipment for making the station an efficient unit from both a technical and commercial stand point. Plant availability is a factor of prime importance and as much depends on the maintenance department it is essential that a sound and adequate staff be chosen.

## ECONOMY IN BOILER AND TURBINE ROOM

### Physical Depreciation

Physical depreciation is the result of wear and tear on the unit in service together with the decay and corrosion due to time and the elements. There comes a time when this increases the maintenance cost with the accompanying decreasing efficiency, due to the increasing frequency and seriousness of the ills of the machine. So increased is the cost of operation that it would be less expensive to pay the costs of a new machine or piece of apparatus. At such a point, the machine has reached the end of its useful economic life.

This situation, in a typical life history, is shown in Fig. 2, Maintenance, Renewal, and Replacement Costs for Delray No. 2 Steam Turbine Plant, for the period 1915 to 1928. The graph is based on the actual costs as shown by the books of account. In this accounting system, current maintenance includes such labor and material, necessary to maintain the plant in a state of operating efficiency, as do not result in a substantial change of identity in any particular

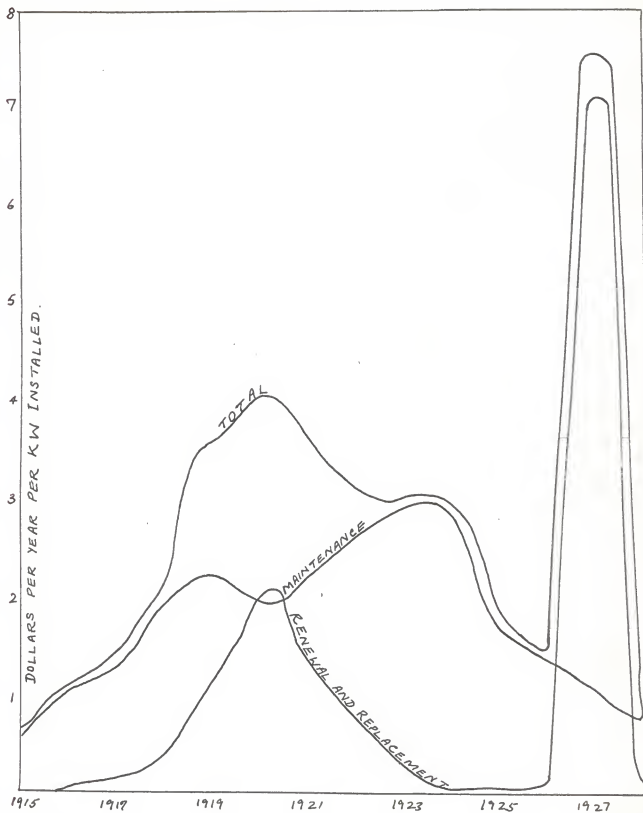


Fig. 2. Maintenance, renewal and replacement costs. Delray steam turbine plant of the Detroit Edison Company.

unit of property. It includes the cost of minor replacements of small parts commonly called the cost of "repairs," but it does not include the cost of replacing entire structures or units of equipment. "Renewal and Replacement" cost includes the cost of the particular unit replaced plus the cost of dismantling it less any salvage value. Examination of the graph shows that on both the maintenance and the renewal and replacement curves for Delray there is a valley during the years 1917 and 1918 whereas peaks occur in 1919 and 1920. This variation is due to the fact that during the First World War and immediately thereafter certain maintenance work had to be deferred, chiefly on account of lack of spare capacity to carry the load. Spare capacity became available in 1920, and then a large amount of work was done. If it had not been for this unusual condition, some work would have been done earlier, which would have resulted in filling up the valley and lowering the peak. Also, the period in question was one of great variations in the prices of labor and material and of change in the amount of work performed by labor. If the figures were further adjusted to allow for the abnormal increases in costs of material and labor and the inefficiency of labor, then the peak of 1920 would be further lowered. After the considerable overhauling in 1920, the plant, of course, was in better operating condition, so the costs for 1921 and 1922 decreased. Also, the prices of labor and material had decreased somewhat.

In an effort to eliminate the effect of price changes on the annual costs of maintenance and replacements, the data of Fig. 2 for Delray were rearranged. The figures for maintenance were divided into 50 percent material, 50 percent labor, and the figures for renewals and replacements were divided, 35 percent for labor and 65 percent for materials on turbine and electrical plants, but 20 percent for labor and 80 percent for materials on boiler plant. The divided amounts were reduced to a 1915 basis by the application of an index number



appropriate to the sub-division for each particular year. The reworked items were then totaled and the cost per kilowatt-year determined. As reconstructed to this uniform basis of price the data are shown in Fig. 3. The remarkable uniformity of the maintenance and renewal costs for the electrical plant is worthy of note, being approximately 5 cents per kilowatt-year for 1915 to 1918, then 10 cents per kilowatt year for 1919 to 1922, after which the maintenance increases sharply, showing the effect of the greater care necessary to keep the old machines in satisfactory operating condition. The turbine costs are also fairly uniform, rising from 10 cents per kilowatt-year in 1915 to 25 cents per kilowatt-year in 1921, and again in 1924. In the boiler plant, however, the costs are not only variable but are many times those of the turbine department. A boiler, for instance, operates with gradually increasing maintenance costs for several years until the settings have to be replaced, at which time it is usually given a thorough overhaul and put into as good condition as is possible. This causes a peak in the cost curve of that individual unit which will be followed by a valley, because after the thorough renovation the maintenance will drop off for a period. In a large plant, of course, units will be in all conditions of upkeep, and the peaks and valleys would hardly be noticeable. The renewal and replacement cost curve on the boilers illustrates this variation quite typically. It starts at 13 cents in 1915, falls to 2 cents in 1916, then rises more or less gradually to a maximum of 100 cents in 1920, and then decreases to zero in 1924. At the time of peak replacement cost of 100 cents in 1920, the maintenance cost is at a minimum of 65 cents per kilowatt-year. The shape of the total cost curve is almost identical with that of the boiler curve, since the latter makes up such a large part of the total cost.

As is noted in Fig. 2, Delray power plant No. 2 did not operate at full capacity after 1924 but served mainly as stand-by capacity for peak load periods.

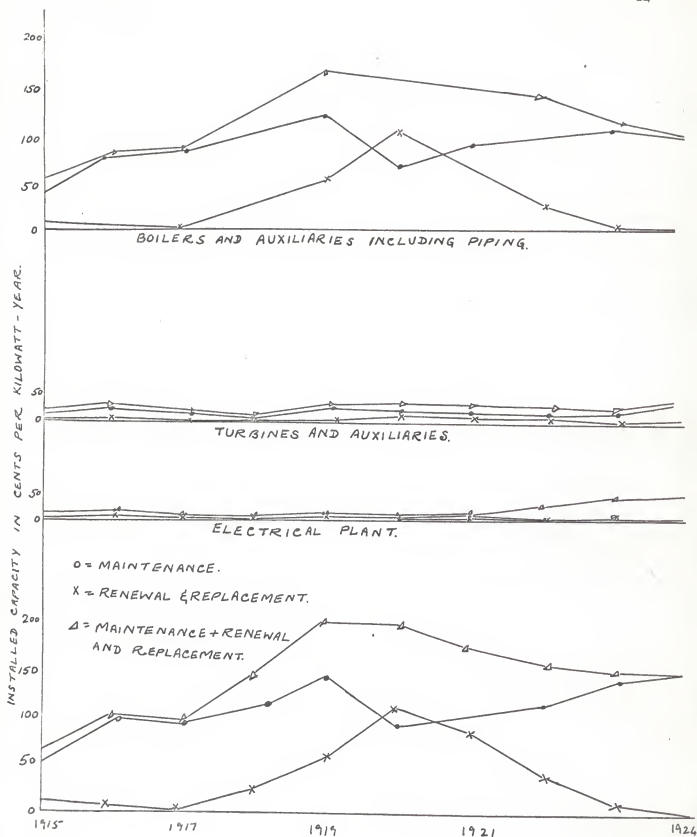


Fig. 3. Maintenance, renewal and replacement costs.

For such a purpose, the station average load was about half the rated capacity, so that a number of boilers and turbines were in reserve and the maintenance correspondingly reduced.

### Obsolescence

There are certain types of fixed costs sometimes assumed which should not enter into the engineer's calculations, though they do involve a very real charge against the investment necessary to do business. One of these is due to obsolescence - the state of becoming old-fashioned or out of style - which may easily enough occur well within the reasonable physical life of the apparatus. Obsolescence indicates that, as a result of engineering achievement, the present apparatus, whether it be as one piece or a whole class, has become uneconomical of use. The field of power generation and distribution has developed so rapidly that larger and more efficient machines and methods are constantly being developed. Whether the present equipment should be replaced before it is worn out depends upon the amount of the saving in operating expenses which the modern equipment could effect as against the increased fixed charges due to its purchase and the retirement of the old units. It may be the case, for instance, that a steam turbine installed now will, in 10 years, be too expensive to operate because of advances in turbine design which have made the model of 10 years hence much more economical than that of the present.

### Supersession Due to Physical Decay

In spite of repairs and renewals of parts, the age and physical decay increase so that physical property eventually reaches a stage where it will be more advantageous to abandon the plant than to continue with the repair. With some kinds of property, this depreciation occurs with the passage of time

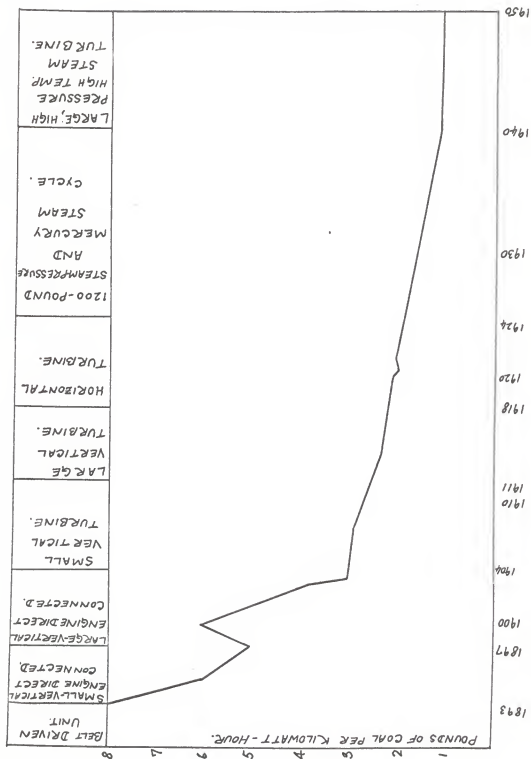


Fig. 4. Prime mover development and improvement in production efficiency 1890 to 1950. (Detroit Edison Company)

whether the property is in or out of use. For example, the insulated wires and cables carrying current have covering layers of cotton, rubber and other materials which deteriorate with age and with exposure to the weather. Thus, entirely aside from supersession due to inadequacy or obsolescence, investigation must be made from time to time to ascertain whether the plant or apparatus is worn out or has reached the limit of its economic life. If supersession is postponed, there will be an increasingly longer time in which to collect the depreciable part of the investment, and the yearly cost of this accumulation will be less and less.

There will be the fixed charges of taxes, insurance, and money use. Since we have already made our original investment, and since we are not at this time considering any changes in the design of our machinery, these three costs may be considered as constant and will not affect our judgment in either direction.

To determine the economically ideal time for supersession, due to economic decay alone, we may write a cost equation that involves all these factors:

$$\$ \text{ per year} = O + (\text{taxes} + \text{insurance} + e) P + A_n (P - S_n)$$

where \$ = total annual cost.

$O$  = equivalent uniform annual operating expense.

$e$  = annual rate earned on the accumulation or depreciation reserve.

$eP$  = cost of money use on the investment.

$S_n$  = expected final scrap value.

$A_n (P - S_n)$  = annual accumulation to the depreciation reserve to care for the depreciable part of the investment.

As here used,  $A_n$  is the annual accumulation rate based on the "actual" life of the machine, not on the estimated life.

By differentiating with respect to time and equating to zero, we shall find the point of ideal cost; i.e., the point at which supersession should occur. The second term of the right-hand member being a constant will drop out, and we have

$$\frac{dS}{dt} = \frac{dO}{dt} + A_n \frac{d}{dt} (P - S_n) + (P - S_n) \frac{d}{dt} A_n \quad (1)$$

$$= \frac{dO}{dt} - A_n \frac{d}{dt} S_n + (P - S_n) \frac{d}{dt} A_n = \text{Zero for a minimum cost.} \quad (2)$$

Simplifying the third term and putting

$$A_n = \frac{e}{(1 + \frac{e}{2})^{2t} - 1}$$

where  $t$  is the time in years,

$$\frac{d A_n}{dt} = \frac{-e (1 + \frac{e}{2})^{2t} \cdot 2 \log (1 + \frac{e}{2})}{(1 + \frac{e}{2})^{2t} - 1} \quad (3)$$

Rearranging this in parts, then

$$\frac{d A_n}{dt} = \frac{-e}{(1 + \frac{e}{2})^{2t} - 1} \frac{(1 + \frac{e}{2})^{2t} - 1 + 1}{(1 + \frac{e}{2})^{2t} - 1} \cdot 2 \log (1 + \frac{e}{2}) \quad (4)$$

$$= -A_n (1 + \frac{A_n}{e}) \cdot 2 \log (1 + \frac{e}{2}) \quad (5)$$

Expand the last term by Maclaurin's series, and

$$\frac{d A_n}{dt} = -A_n (1 + \frac{A_n}{e}) e \cdot 1 - \frac{e}{4} + \frac{e^2}{12} - \frac{e^3}{32} + \dots \quad (6)$$

or since the value of  $e$  is generally in the neighborhood of 0.06 the bracketed terms become, respectively,

$$1 - \frac{0.06}{4} + \frac{0.0036}{12} - \frac{0.000216}{32} + \dots$$

which are

$$(1 - 0.015 + 0.0003 - 0.000007 + \dots)$$

$$\text{and } \frac{d A_n}{dt} = -A_n (e + A_n), \text{ approximately} \quad (7)$$

It is also noted that  $\frac{d S_n}{dt}$  will, in general, be negative, since the



salvage value decreases as time goes on. Substituting the value of  $\frac{d A_n}{dt}$  from eqn. (7) in eqn. (2) gives

$$\frac{d S}{dt} = \frac{d O}{dt} - A_n (P - S_n) (e + A_n) + \frac{d S_n}{dt} \quad (8)$$

in which the sum indicated within the brackets will be an arithmetical difference. If the value of the equation is zero, then the ideal time for supersession has just been reached; if the value exceeds zero, the ideal time has passed, and if the value is less than zero, the ideal time has not yet been reached.

The application of this criterion to any particular instant of time is a comparatively easy matter. The first term may be evaluated directly, for  $n$ ,  $P$ , and  $S_n$  are known for that date. The term  $\frac{d S_n}{dt}$  may be conveniently determined by plotting the different salvage values against the times at which they occur and graphically finding the slope of the tangent to the curve at the point in question. In the determination of  $\frac{d O}{dt}$ , however, another method should be used.

#### Developments in Fuel Burning Plants

**Steam.** The history of fuel burning plants in the electric light and power industry is one continuous story of increases in the capacity of its prime mover sets together with marked gains in the thermal efficiencies.

With the advent of the steam turbine, however, the engine was rapidly superceded as a large prime mover in electric stations. The decisive advantages of lesser floor space, high economy under wide range of loads, ease of application with superheated steam, freedom from oil in the condensate, and the uniform angular velocity were so compelling that the change was made very quickly.

Table 1 shows typical heat rates for various sizes of turbines under their particular operating conditions. As better materials become available, the improved designs utilize higher blade speeds which result in a great saving of

Table 1. Average consumption of fuel per kilowatt hour by power plants.

Year	Consumption of fuel, equivalent, millions of tons	Production by fuel, millions of KW hr.	Lb. per KW hr.
1921	34.92	25,864	2.70
1923	43.31	36,088	2.40
1925	45.43	43,268	2.10
1927	46.00	50,001	1.84
1929	52.64	62,295	1.69
1931	47.11	60,791	1.55
1933	37.15	50,546	1.47
1935	43.20	59,176	1.46
1937	55.14	76,883	1.43
1939	59.51	85,800	1.39
1940	62.94	93,963	1.34
1941	75.70	113,272	1.34
1942	79.08	121,585	1.30
1943	93.27	143,785	1.30
1944	99.25	153,868	1.29
1945	92.64	142,331	1.30
1946	93.47	144,555	1.29
1947	115.67	176,983	1.31
1948	130.12	199,796	1.30
1949	127.06	200,965	1.26
1950	137.61	226,027	1.22

From Electric Power Statistics, by the Federal Power Commission, Elec. World, January 29, 1951.

weight and reduction in the size of the turbine.

The gain in the thermal efficiency for power plants as a whole is well shown by the pounds of fuel per kilowatt hour in Table 1.

#### How to Avoid Extravagant Use of Boilers

Curves plotted in Fig. 5 to show the results of operation in both the turbine room and the boiler room are used by the engineers and managers of an Indiana plant as a check against extravagant operation of boilers. The curve is arranged so that the number of boilers in service and the load on the plant in kilowatts are plotted versus time. By using the same abscissa for both curves and by choosing a proper ordinate scale the curves fall very near together if proper operation is obtained. Any variation from normal is at once noticeable, owing to the wide divergence which the lines show. When this occurs, the manager generally demands an explanation from the chief of the boiler room. There must always be a good reason for carrying more boilers than the chart indicates are necessary.

Data from which these curves are plotted are collected separately by the man in charge of the boiler room and the man in charge of the engine room. The relation of the two curves to each other is therefore known to the boiler room chief only after he has turned in his data. To assist the boiler room chief in holding just the right number of boilers on the line, or in readiness to go on, it was of course necessary to place in the boiler room a totalizing watt meter to indicate the station load.

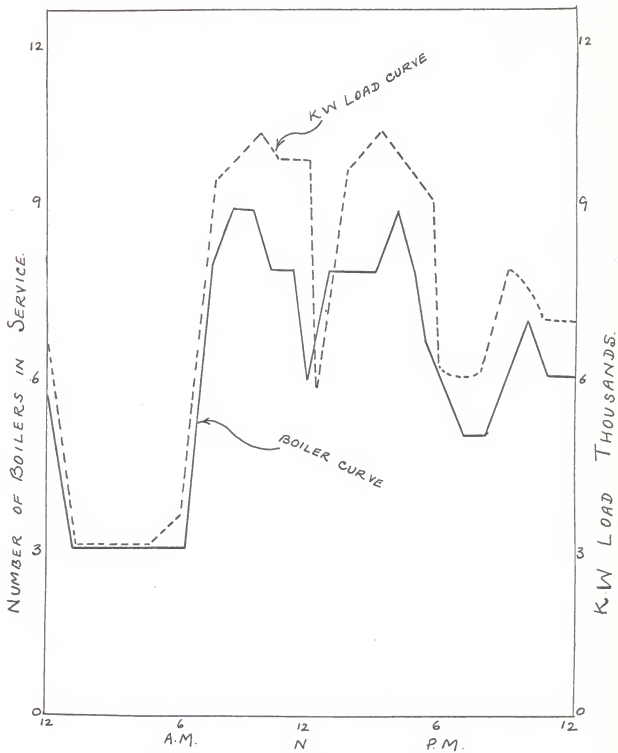


Fig. 5. Boiler curve should nearly coincide with KW load.

## ECONOMIC OPERATION OF ELECTRICAL PLANTS

### Methods of Rating Alternators

Two methods of rating turbo-alternators based upon temperature rise are adopted - the maximum continuous rating and economical rating. The maximum continuous rating indicates the highest loading at which the set may be run continuously, while the economical rating indicates a loading above which there is an overload capacity. The most economical output is not based on temperature rise and refers to the turbine on the combined unit. The following is a typical specification clause:

"The alternator and exciter shall be capable of running at a continuous maximum rated output of 50 MW at any power factor between 0.8 lagging and 0.8 leading and also at an economical-rated output of 40 MW at any power factor between 0.8 lagging and 0.8 leading with a cooling air temperature of 40°C. without the temperature of any part attaining such a value as to effect the permanence and insulating properties of the winding and without the observable temperature rises in any part exceeding those given in the appropriate standard specification."

### Improving Power Factor and Voltage Regulation

As the company expands and the load on the system increases, it will very likely continue to place synchronous condensers at the principal load centers, and the time may come when it can obtain practically a flat voltage curve not withstanding variations in the power factor.

A little analysis on the part of the operator who is pressed for sufficient plant capacity may reveal the fact that by the use of a synchronous condenser he can secure some, if not all, of the following benefits:

1. Meet increased demands without the purchase of additional generating equipment - and by generating equipment is meant not only the generators but the necessary prime movers and auxiliary apparatus.

2. Reduce the cost per kilowatt of additional transmission rating.

3. Effect a material saving in present transmission losses.

4. Improve service by maintaining the required voltage.

To accomplish the desired results at minimum expense, and at the same time provide for probable future increase in load, it was found, in view of the low power factor, that the installation of a synchronous condenser for corrective effort would actually reduce the transmission investment required per kilowatt, so that a condenser at this point was warranted on the basis of transmission rating alone.

Figures 6 and 7, prepared from the transformer and line characteristics, will show the voltage compensation, or regulation, which can be obtained, the line amperes and the line power factor as follows:

(a) Inherent regulation, two lines in parallel, 0 to 16,000 KVA: 70% power factor.

(b) Inherent regulation, one line, 0 to 7750 KVA, 70 percent power factor.

(c) Range of constant voltage obtainable when using synchronous condenser from maximum lagging KVA to maximum leading KVA.

(d) Synchronous condenser loads, one line in service.

(e) Synchronous condenser loads, two lines in service.

(f) Maximum load transmitted 7500 KW, both lines in service maximum power factor 100 percent.

(g) Voltage range corresponding to curve (f).

There are several fixed adjustments which can be used to add to the voltage regulation as conditions materially change: (1) the ratio of transformers may be



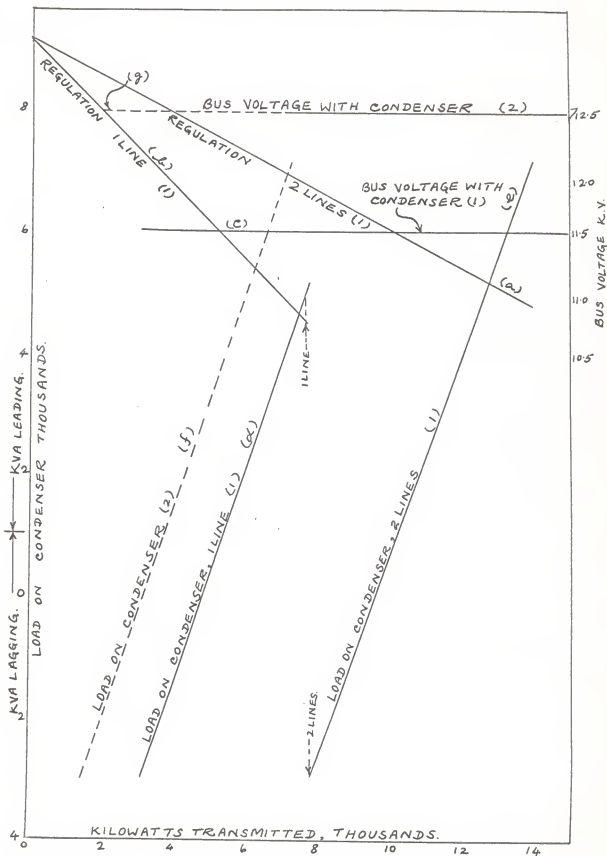


Fig. 6. Load and regulation curves. (From Cutting Central Station Costs by S. B. Williams.)

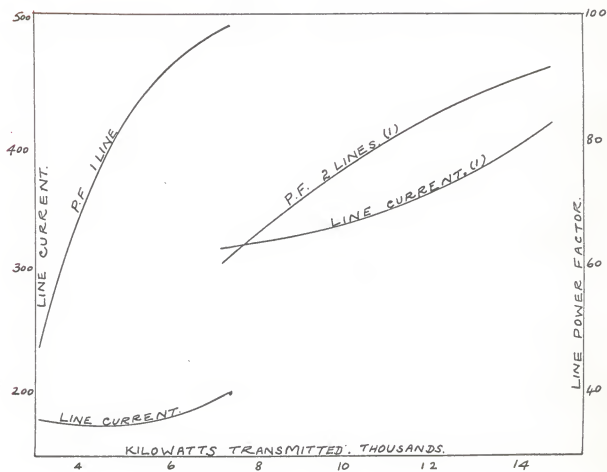


Fig. 7. Line current and power-factor curves.

changed; (2) one line or two lines may be used; (3) the old 11000-volt tie line having approximately 20 percent regulation can be connected on exceedingly light loads.

With one line in service and using the maximum limits of the condenser it will be noted from curves (c) and (d) that the voltage can be maintained constant with load varying from 3100 KW to 7400 KW. Under load of 7400 KW the maximum capacity of one line is reached, so at this point the second line is put in service, as shown by the arrows and dotted lines at curves (d) and (e). When the two lines are operated in parallel and using the condenser between its limits, constant voltage is obtained with load varying from 7400 KW to 14,400 KW, as indicated by curves (c) and (e). With load of 14,400 KW and condenser operating at maximum capacity leading, the power factor of the line is at its maximum - 90 percent - and the lines are fully loaded at 16,000 KVA. When the maximum load is only 7500 KVA and 100 percent power factor is obtainable, it will be noted that flat voltage range is materially increased, but since the allowable drop is reduced the transformer ratio must be changed.

While the curves show the limits of constant voltage with the condenser in service, it should be noted that it is very undesirable to run the machine at lagging power factor, since it reduces the power factor of the plant, which is already objectionably low. Upon referring to power factor curves, especially the one for one line, it will be seen how rapidly the power factor drops when the condenser is drawing lagging current.

#### How to Reduce Cost of Station Regulator

Conditions with the Dayton (Ohio) Power and Light Company made it seem necessary to regulate the voltage on circuits supplying station lighting in the new power house at Miller's Ford. To keep from buying a high-voltage regulator

to operate at the generator potential of 6600 volts, the scheme of connections illustrated in Figure 8 was developed.

From the 6600 volt bus these circuits were taken through the 200 KVA, 6600/230 and 115 volt transformer which fed all station lighting circuits. In the outside lines of the three wire secondary of this unit was connected a series boosting transformer with a ratio of ten to one as in Figure 8, the high voltage winding being designed for 230 volts and the low voltage for a total of 23 volts, 11.5 volts in each half. The high voltage winding of the boosting transformer receives from 0 volt to 230 volts from one winding of a low voltage one-to-one ratio induction regulator, the other winding of the regulator being energized from the outside lines of the secondaries of the main 200 KVA transformer. Connections to the contact making voltmeter as shown completing the circuit. The unit is now operating satisfactorily.

#### Increasing Generator Rating by Precooling Ventilating Air

The question of whether to install air washers or humidifiers for conditioning and cooling the air entering generators is particularly pertinent at this time, writes Joseph T. Foster of the Public Service Electric Company of New Jersey, since by cooling this air the generator capacity may be increased from 10 to 20 percent. Furthermore, by cleaning the air, possible shut-downs for generator cleaning and, what is more serious, possible burnouts due to heavily loaded, dirty machines, may be avoided. Obviously, then, this is the quickest and cheapest method of increasing power.

The purpose of central station companies in including the air washer as standard equipment on turbo-generator installations is two-fold:

1. For supplying clean air, free from dust which would coat the windings of the generator and form an insulating covering.

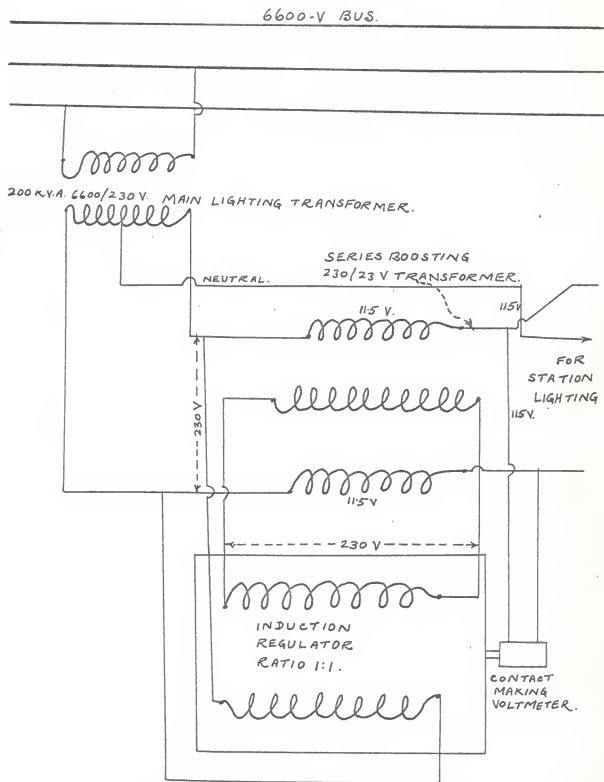


Fig. 8. Regulator arrangement made to avoid buying high voltage unit.

2. For pre-cooling the air by evaporation of water when the air passes through the film of water atomized by the spray nozzles.

Before air washing equipment was used it was found that the dust and dirt incidental to the unloading of coal and the disposal of ashes fouled the generator by coating the air passages. It was therefore necessary to shut down the generator at least once a year for a period of five or six days for cleaning purposes. In addition to the expense of cleaning, there was the inconvenience and loss of revenue due to shutting down the unit.

Some idea of the cleansing effected by a modern type air washer can be gained from tests which showed that it was possible to blow several pounds of soot per minute into the intake and have the air at the generator inlet perfectly free from dust.

There is a more or less widespread belief that the humidifying of the air increases its cooling capacity on the grounds that wet air, on account of its higher specific heat, has greater heat-absorbing properties.

#### Inexpensive Method of Increasing Line Capacity

To provide for growth in load the New York and Queens Electric Light and Power Company, Long Island City, New York was confronted, not long ago, writes H. C. Dean, General Superintendent, with the problem of increasing the rating of its distribution circuits about 30 percent.

Choice of Systems: Three methods of solving the problem were open: (1) to install additional two-phase feeders (2300 volts, four wire); (2) to install high-tension feeders and relieve the 2300 volt feeders of the large consumers; (3) to change the 2300 volt, two phase system to 2300/4000-Y volts, three phase.

The chief question at first was whether or not it would be as inexpensive to change from two phase to three phase as to leave the two-phase system and



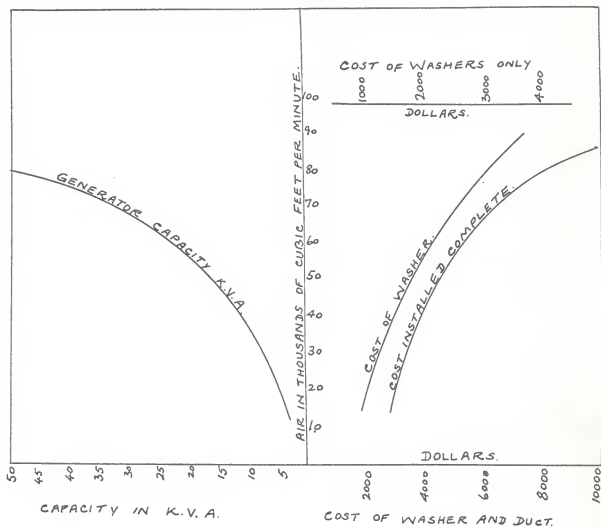


Fig. 9. Relation between KVA rating, amount of cooling air required per minute, cost of air washer installed complete.

transfer the larger consumers to lines operating at transmission voltage. A number of consumers are so supplied at the present time, and the company is looking forward to increasing such services to a large extent from now on. With the existing geographical layout of the lines and large consumers, the arguments were two to one in favor of changing the two-phase distribution system. However, this was due to local conditions, and it is possible that for other companies the advantages would be materially different, either greater or less.

Careful estimates showed that the third alternative would provide the necessary rating for less than half the expenditure required by the other methods owing chiefly to the high cost of copper. It had the additional advantage that any future feeders would have 50 percent greater capacity as three phase feeders than as two phase feeders, while the percent time loss and voltage drop would be only half as great. To determine the relative advantage of three phase over two phase, it was therefore only necessary to determine the valuation of the existing distribution system (less the poles) and to balance 50 percent of this cost against the cost necessary to change to three phase.

In the Long Island City district the power load is about four times as large as the lighting load, consequently considerable work had to be done in making changes in the transformer banks. Although new consumers are provided with three phase service, it was decided to continue two phase, 230 volt service to existing consumers. This made it necessary to replace one transformer of each power bank with two of half the rating having 10 percent taps. The connections and the voltages obtained are shown in Figure 10.

There are no theoretical disadvantages in this method, as far as Mr. Dean can see and it has given entire satisfaction.

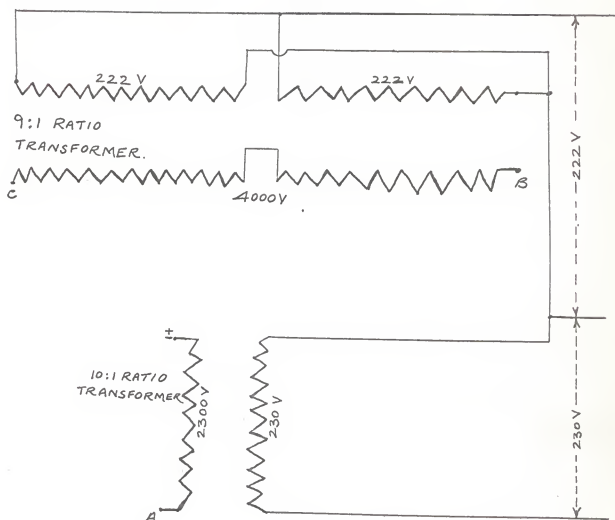


Fig. 10. Method of converting from two to three phase with standard transformer.

## POWER PLANT LOAD CURVES AND OTHER FACTORS OF ECONOMY

Cost of power as affected by plant factor: obviously the fixed charges accumulate steadily on the total installed capacity in the station. If it were possible to utilize each kilowatt of capacity for all the 8760 hours of the year, each kilowatt hour would carry only  $1/8760$ th part of the fixed charges on the kilowatt, but if the utilization covers only 4380 hours of the year, then each kilowatt hour must carry twice the former charge; therefore the cost varies inversely as the plant factor. It should be noted that the plant factor; i.e., the ratio of the average annual load to the rated capacity, is the proper one to use in this connection, not the annual load factor.

The load factor for the plant or system is the ratio of the average power to the peak power for a certain period of time. The peak power is generally taken as that prevailing for a half hour period, and the average load may be that in a period of one day, one month or one year. If the maximum load corresponds exactly to the plant rating, then the load factor will be identical with the plant factor. The utilization factor, defined by the American Standards Association as the ratio of the maximum demand of a system or part of a system to the rated capacity of the system or part of system under consideration, is another important item in power plant operation.

In the operating items, fuel and labor costs increase per unit of energy with decrease of plant factor, although operating repairs are probably independent of plant factor. At light load, not only must the fuel used be sufficient to supply that load, generally at a poor efficiency, but also auxiliaries of a capacity for much greater load must be run and fires must be banked under sufficient additional boilers to provide a capacity for the peak load of the day.

A most interesting analysis of the cost of power for any given load curve

at the various hours of the day may then be made by obtaining the load values at different hours. As an example, Figure 11 shows the system peak winter curves. The average load for the day is 64 percent of the peak load, but for almost 10 hours of the day the load is below this average value, and for nearly five hours of the day the load is only 30 percent of the maximum value. Hence, according to the relative values per kilowatt hour shown, the cost of energy per unit will be very much higher for the light loads of the morning hours than for the more heavily loaded part of the day. For this reason, the manager of a commercial power company should make a special effort to find customers who can use energy in the valley periods and to build up the load factor and decrease the cost of production.

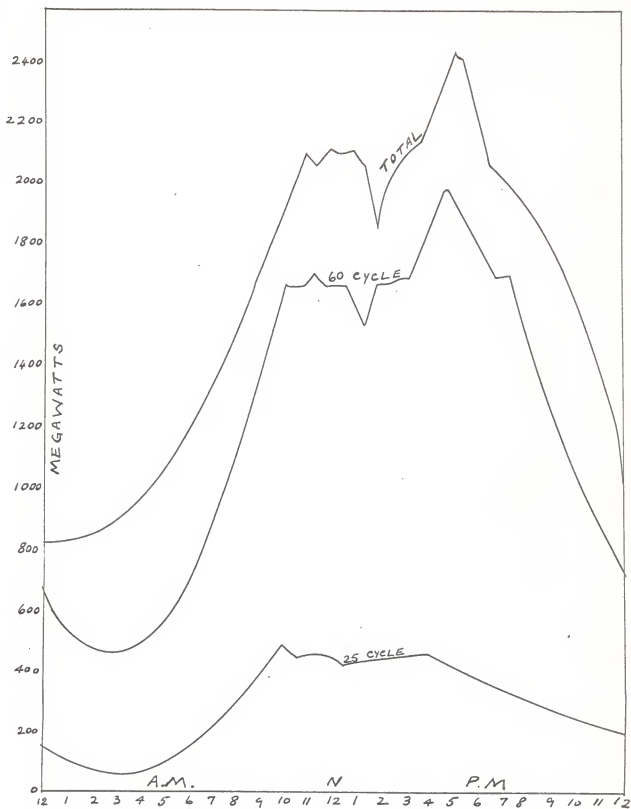


Fig. 11. Load curve of Consolidated Edison System, New York, for Monday, December 12, 1949. Mean temperature 52°F. Rain all day. Load factor 64%.

Table 2. Cost of steam-electric generation for various plant factors.

Fixed charges 12.5 percent. Cost per KW complete, \$100, mo. reserve							
Yearly fixed charges per KW installed \$12.5							
B.T.U. per KW hr. = 10500 + (30000/% plant factor)							
Coal = 14000 B.T.U. per lb.							
Plant factor percentage	100	80	60	40	30	20	10
Hours of use	8760	7008	5256	3504	2628	1752	876
Fuel per KW hr., lb.	0.773	0.777	0.786	0.804	0.821	0.857	0.964
Charges, cts. per KW hr:							
Fixed	1.43	0.178	0.238	0.357	0.475	0.714	1.429
Other, except fuel	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Total all charges except fuel	0.223	0.258	0.318	0.437	0.555	0.794	1.509
Cost of coal, dts. per KW hr.:							
Coal at \$1 per long ton	0.0345	0.0347	0.035	0.0358	0.0366	0.0382	0.043
Coal at \$3 per long ton	0.1035	0.1041	0.105	0.1074	0.1098	0.1146	0.129
Coal at \$5 per long ton	0.1725	0.1735	0.175	0.1790	0.1830	0.1910	0.215
Total cost, cts. per KW hr.:							
Coal at \$1 per long ton	0.2575	0.2927	0.353	0.4728	0.5916	0.8322	1.552
Coal at \$3 per long ton	0.3265	0.3621	0.423	0.5444	0.6648	0.9086	1.638
Coal at \$5 per long ton	0.3955	0.4315	0.493	0.616	0.738	0.985	1.724

From Progress in the Generation of Energy by Heat Engines, by George A. Orrok, Trans. ASCE, 1939.



## Effect of Temperature Upon Service Life of Equipment

The AIEE standards assign temperature limits under which the various classes of insulation may reasonably be expected to retain the proper electrical and mechanical characteristics for operation. These give the "hottest spot" temperature for class O material (cotton, silk, paper, etc.; not impregnated or immersed) as 90°C; Class A material (organic materials, impregnated or immersed) as 105°C; Class B material (mica, asbestos, fiber glass, inorganic materials) as 130°C. The temperature limits of insulation are not the only factors determining how much load a machine may carry. This will depend upon the weakest link in its structure and may be in mechanical parts, slip rings, brush capacity and commutation in d.c. machines, cable connections, etc. However, granted that these elements have been designed and are maintained adequate for the maximum duty involved, increasing the load will raise the temperature and shorten the life of insulation. The upper line in Figure 12 shows "the 10 deg. life curve" because insulation life is halved by each 10° increase in temperature was evolved about 1925 and represents the insulation in air. The lower line, "the 8 deg. curve," brought out by V. M. Montsinger of the General Electric Company about 1930, was established by tests of insulation immersed in oil. Slight traces of acid in the oil have a pronounced effect upon the life of the insulation.

### High-grade Coal Fired During Peak Load Periods

Influx of war industries coupled with slow deliveries of equipment made the problem of carrying peak load a difficult one for the Moline plant of the Moline-Rock Island Manufacturing Company, which supplies electric service to the "Tri-Cities," Davenport, Rock Island and Moline. Boiler capacity appeared to be the limiting factor. In order, therefore to obtain the maximum rating out of

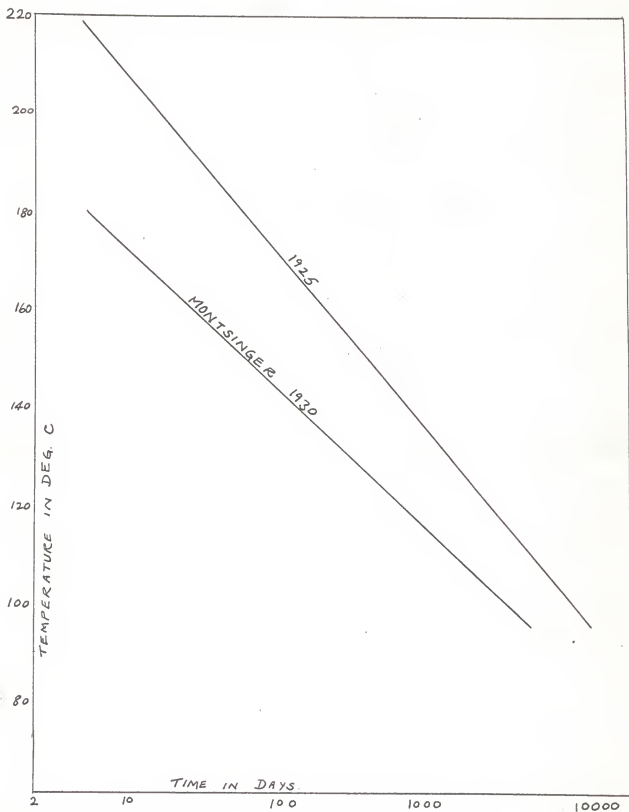


Fig. 12. Temperature-life curve for class 'A' insulation.

the existing equipment only high-grade coal was burned during peak hours. Under ordinary conditions Iowa coal was burned.

Getting the high-grade fuel on the fires at the critical time was the chief problem. The difficulty was surmounted by constructing auxiliary bunkers for the high-grade southern Illinois coal. They were constructed of wood and were set almost against the fronts of the 500 hp. boilers in an elevated position so that they could be emptied into the stoker hoppers during peak loads by operating a metal-bound wooden gate. The clearance between these bunkers and the boiler fronts was just sufficient to afford ventilation and to give space for operating levers. The auxiliary bunker in front of each 500 hp. boiler holds three tons of coal. Coal was delivered to these auxiliary hoppers by the same machinery that conveyed coal to the overhead bunker that holds the supply of ordinary coal. When the high grade coal had to be distributed, chutes were arranged under the conveyor so that the coal would be dumped into the auxiliary bunkers instead of the main bunker. With underfeed stokers it was possible to get as much as 300 percent of rating out of the boilers with this arrangement, but with the chain-grate stokers 175 percent of boiler rating was about the limit that could be obtained.

#### Method for Maintaining Plant Efficiency

Because of the efficiency measured in kilowatt hours at the switch board per unit of fuel oil used varies with the temperature of the condenser circulating water, the Houston (Texas) Lighting and Power Company was obliged to find some method of comparison for informing the station engineer whether or not he was operating the plant to obtain the best results. The water is obtained from a bayou which is a sluggish stream and which becomes very warm during the summer months. The variation in efficiency is a function of the circulating

water and, according to Frank G. Frost, general superintendent of the company, the summer and winter loads have been very carefully analyzed to get average values. From the steam curve of the turbines a "bogie" curve as seen in Figure 13 has been worked out which gives the relation between the station inputs with variable circulating-water temperatures. The percentage that each day's results are above or below this curve is posted in the station turbine room so that the operators at all times are familiar with the actual economics of the station. Fuel oil and meters are read hourly.

#### Saving in Cost Due to Inter-connection

Under present practice any new station of a public utility power system has come into being, not as a single individual power producer by itself, but as a new element joining other established and operating stations on the system. Ties were immediately established between such a new plant and all the others or between the more important plants of the system, so that power might be transmitted from station to station or from any station to the transmission network within the same system. In this way, the generating station and the transmission system combine into the single problem of power supply. But in addition to company ties, by the establishment of inter-connecting lines from the transmission network of the foregoing power system to that of an adjoining power system or systems, the new station may send or receive power to or from other power companies. Thus the total amount and diversity of the available reserve power to ensure reliability of service are enormously increased, and a sufficient power reservoir may eliminate entirely the installation of spare units in the new station with the consequent burden of their fixed charges. As regards the whole system, each may dispense with some portion of the reserve capacity, which it would otherwise carry, through this pooling of the reserves.

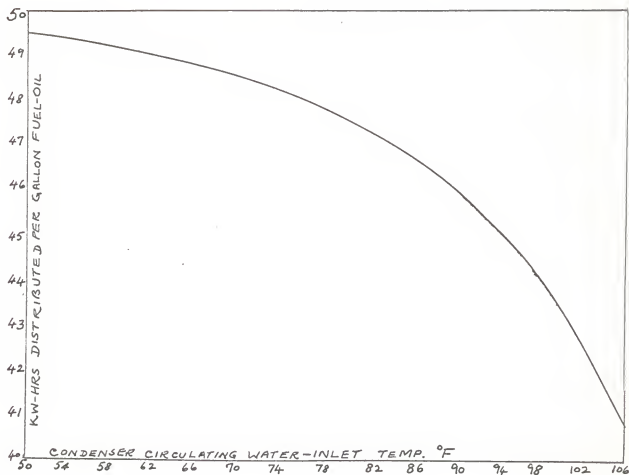


Fig. 13. Curve for power plant efficiency used as standard.

## CONCLUSION

This paper has briefly pointed out the factors which will considerably reduce the operating cost of any modern electric power generating station. Every care has been taken to maintain the continuity of power supply.

In practical life, it is very difficult to apply all of these economic factors to any one generating station. However, quite a few of these factors will be found to be of immense use to any generating station. The application of these factors depends mainly upon the various other elements of the station itself, such as the station design, generator ratings, peak and average load, hours of peak load, growth of load, inter-connection, line capacity, labor employed, cooling system, local climate, availability of coal, and the type of generator, turbines and boilers in use, etc.

If a new station is being built, then, immense consideration must be given to the above factors, which will be found to be of considerable use in the long run over the system as a whole.

## ACKNOWLEDGMENT

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ECONOMIC OPERATION OF ELECTRIC POWER SYSTEMS

by

Chandru Jethanand Bhajwani

B.S., Vikram University  
India, 1963

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AN ABSTRACT OF  
A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY  
Manhattan, Kansas

1965

In these days of rapid electrical development, the power station is probably the most important part of an electricity supply undertaking.

The widespread use of electricity for the benefits of a community has been made possible by the continued efforts of engineers to take full advantage of its possibilities.

Its advantages are well known, and it is the duty of engineers to give an abundant and reliable supply of electricity at the lowest possible price. The transmission of large amounts of electrical power over wide areas is economical and practicable, and this in turn has had a decided effect on the choice of power station sites. The continual advantages in generation, transmission and distribution plant also play important parts in power station design.

In this paper, an attempt has been made to point out the factors which will greatly reduce the cost of every unit of electricity generated. The first section deals with the essentials and economic design. Here several factors for a good and economic design have been considered. Attention has also been paid to the availability of labor, coal, water, extensibility and organization, etc.

The next section deals with cutting costs in boiler and turbine room. Obsolescence, physical depreciation, supersession due to physical decay, developments in fuel burning plants and avoiding the extravagant use of boilers are the main elements which are discussed.

Attention has been paid to the economic operation of electrical plants in the next section. This section deals mainly with the methods of rating alternators, power factor improvement, voltage regulation, increase in generator efficiency by pre-cooling ventilating air and the inexpensive method of increasing line capacity.

The paper closes with the final section on load curves and other factors of economy. This section suggests the study of load curves for obtaining a

considerable economy. It also points out the temperature and life relation of equipment, saving in cost due to inter-connection, and a method for maintaining the plant efficiency, etc.